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Comparative Exhaust-Gas Characteristics of Sugarcane Bagasse and Pineapple Waste Bioethanol Blends in a Fuel-Injected Motorcycle under a Common HHO-System Configuration

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ABSTRACT

Agricultural waste-derived bioethanol offers a renewable gasoline-blending option for spark-ignition engines. This study compared sugarcane bagasse- and pineapple waste-derived bioethanol blends in a fuel-injected Honda BeAT motorcycle operated under a common HHO-system configuration. Five fuel formulations—E0, E5-SC, E10-SC, E5-PW, and E10-PW—were tested at 1500, 4000, and 7000 rpm. CO, HC, CO_2, and O_2 were measured using a four-gas analyzer, while λ and AFR were reported by the analyzer. Results are presented as means from three replicate runs. E10-SC recorded the lowest mean CO concentration at 4000 rpm and the lowest mean HC concentration at 7000 rpm, whereas E10-PW recorded the lowest mean CO concentration at 7000 rpm. The formulation rankings varied with engine speed and measured parameter. Because HHO was not tested independently, its specific contribution could not be determined.

Keywords
Sugarcane bagasse bioethanol; pineapple waste bioethanol; exhaust-gas characteristics; fuel-injected motorcycle; HHO-assisted operation

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INTRODUCTION

Gasoline-powered motorcycles are widely used for daily transportation, but their spark-ignition engines emit pollutants, particularly carbon monoxide (CO) and unburned hydrocarbons (HC). These emissions are primarily associated with incomplete combustion and are influenced by fuel properties, air–fuel ratio, engine design, and operating conditions [1]–[3]. Consequently, renewable oxygenated fuels have attracted attention as blending components that may reduce fossil-fuel consumption and improve combustion and emission characteristics.

Bioethanol is a widely studied gasoline additive because of its oxygen content and high octane rating. Ethanol blending alters fuel oxygenation, volatility, heating value, evaporation, and mixture formation, which may improve fuel oxidation under certain conditions. However, its effects on CO and HC emissions vary with ethanol concentration, engine technology, control strategy, and engine speed [1], [2]. Therefore, ethanol–gasoline blends should be evaluated under specific engine and operating conditions rather than assumed to provide uniform emission benefits.

The stoichiometric combustion of ethanol can be represented by Equation (1):

$$C_2H_5OH+3O_2 \rightarrow 2CO_2+3H_2O \quad (1)$$

Equation (1) describes complete ethanol combustion, in which carbon dioxide and water are the principal products. In an actual engine, however, local mixture variations, incomplete evaporation, flame quenching, residual gases, and operating conditions can produce incomplete combustion products. The oxygenated nature of ethanol may support fuel oxidation, but its practical influence on CO, HC, carbon dioxide (CO_2), residual oxygen (O_2), lambda (λ), and air–fuel ratio (AFR) remains dependent on the overall fuel–engine interaction [1], [2].

In addition to its use as an oxygenated fuel component, bioethanol can be produced from agricultural residues that would otherwise require disposal or further treatment. Sugarcane bagasse is a lignocellulosic residue composed mainly of cellulose, hemicellulose, and lignin. Its conversion to ethanol generally requires pretreatment, hydrolysis, fermentation, and purification stages to release and convert fermentable sugars [4]. Pineapple-processing waste, including peel, core, and residual juice, contains carbohydrates that can also be converted into ethanol through fermentation [5], [6]. These two feedstocks differ in biomass structure and processing requirements; consequently, the resulting bioethanol samples may differ in properties such as water content, purity, acidity, density, and residual compounds. Such properties can influence blend formation and combustion, although their specific effects cannot be established without direct fuel characterization.

Available reviews and motorcycle experiments have primarily examined the influence of ethanol concentration, engine operating condition, or a single ethanol source [1]–[3]. These studies show that ethanol–gasoline emission responses are configuration-specific, but they provide limited direct evidence comparing bioethanol derived from different agricultural wastes under the same motorcycle, blend ratios, and engine-speed conditions. In particular, a side-by-side comparison of sugarcane bagasse- and pineapple waste-derived bioethanol formulations in the same fuel-injected motorcycle remains insufficiently documented. This comparison is relevant because differences observed between fuel formulations may reflect not only ethanol concentration but also the characteristics of the tested bioethanol samples and their interaction with the engine-control system.

Hydrogen and oxygen mixtures produced through water electrolysis, commonly described as HHO or oxyhydrogen gas, have also been investigated as supplementary combustion gases. Hydrogen has high diffusivity, a wide flammability range, and a high flame-propagation rate, which may alter mixture combustion when introduced into an engine intake system. Previous motorcycle and gasoline-engine studies have reported changes in fuel consumption and exhaust-gas composition following electrolyzer or oxyhydrogen addition [7]–[9]. However, the observed response depends strongly on the supplied gas flow rate, hydrogen–oxygen concentration, electrolyzer current, electrical power consumption, engine load, speed, and injection configuration [8]–[10]. These parameters must therefore be quantified before the independent contribution or energy benefit of HHO supplementation can be determined.

Two boundaries are particularly important in the present research context. First, a controlled comparison is needed to examine whether the tested sugarcane bagasse- and pineapple waste-derived bioethanol formulations produce similar or different descriptive emission patterns under the same motorcycle operating conditions. Second, when the same HHO system is used for all fuel formulations without a non-HHO control and without measurement of gas-production rate or electrical power, HHO cannot be evaluated as an independent experimental factor. It can only be treated as a common supplementary system configuration under which the fuel formulations are compared.

Accordingly, this study aims to compare the exhaust emission characteristics of Pertamax blended with sugarcane bagasse- and pineapple waste-derived bioethanol in a fuel-injected motorcycle operated under the same HHO-system configuration. Five fuel formulations were evaluated: pure Pertamax (E0), 5% and 10% sugarcane bagasse bioethanol blends (E5-SC and E10-SC), and 5% and 10% pineapple waste bioethanol blends (E5-PW and E10-PW). The tests were conducted at 1500, 4000, and 7000 rpm by measuring CO, HC, CO_2, O_2, λ, and AFR. The contribution of this study is a condition-specific descriptive comparison of two waste-derived bioethanol formulations using the same motorcycle, blend ratios, engine-speed conditions, emission-measurement procedure, and HHO-system configuration. The study does not determine the independent effect of HHO supplementation.

METHOD

Experimental Design and Measured Parameters

A comparative experimental design was used to evaluate the exhaust emission characteristics of gasoline–bioethanol blends in a fuel-injected spark-ignition motorcycle. The experimental factors were fuel formulation and stationary engine speed. The response parameters were carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), oxygen (O_2), lambda (λ), and air–fuel ratio (AFR).

Five fuel formulations were evaluated: pure Pertamax gasoline (E0), 5% sugarcane bagasse-derived bioethanol blend (E5-SC), 10% sugarcane bagasse-derived bioethanol blend (E10-SC), 5% pineapple waste-derived bioethanol blend (E5-PW), and 10% pineapple waste-derived bioethanol blend (E10-PW). All fuel formulations were tested using the same motorcycle, target engine speeds, measurement procedure, and HHO-system configuration. Therefore, the experiment was designed to compare the fuel formulations and did not determine the independent effect of HHO supplementation.

The experiments were conducted using a 2014 Honda BeAT FI CBS motorcycle equipped with a four-stroke, single-cylinder spark-ignition engine and an electronic fuel injection system. The engine had a displacement of 109.5 cm^3 and a compression ratio of 10.0:1. The motorcycle was maintained in its standard factory configuration without internal engine modification. Its main technical specifications are presented in Table 1.

Table 1. Technical specifications of the test motorcycle

Parameter	Specification
Manufacturer	Honda
Model	BeAT FI CBS
Year	2014
Engine type	Four-stroke, single-cylinder, spark ignition
Fuel system	Electronic fuel injection
Displacement	109.5 cm^3
Compression ratio	10.0:1
Cooling system	Air-cooled
Transmission	Automatic continuously variable transmission

The motorcycle served as a small-capacity fuel-injected test platform for examining formulation-specific exhaust-gas responses under controlled stationary engine-speed conditions [3].

Fuel Materials and Blend Preparation

The base fuel was commercial Pertamax gasoline with a research octane number of 92. Two bioethanol samples derived from sugarcane bagasse and pineapple waste were used as blending components. Both samples were reported to have an ethanol purity of 95%. The method, measurement basis, and procedure used to determine this reported purity were not available in the experimental record; therefore, the value was treated as reported sample information rather than an independently verified fuel property.

The blends were prepared on a volumetric basis. E5 formulations contained 5% bioethanol and 95% Pertamax, whereas E10 formulations contained 10% bioethanol and 90% Pertamax. After preparation, the fuel formulations were stored in closed containers before testing. The volumetric composition and bioethanol source of each formulation are summarized in Table 2.

Table 2. Volumetric composition and bioethanol source of the test fuels

Fuel code	Fuel composition	Bioethanol source	Ethanol content
E0	100% Pertamax	None	0%
E5-SC	95% Pertamax + 5% bioethanol	Sugarcane bagasse	5%
E10-SC	90% Pertamax + 10% bioethanol	Sugarcane bagasse	10%
E5-PW	95% Pertamax + 5% bioethanol	Pineapple waste	5%
E10-PW	90% Pertamax + 10% bioethanol	Pineapple waste	10%

These formulations enabled comparisons between two nominal ethanol concentrations and two waste-derived bioethanol sources while retaining Pertamax as the same base gasoline. Related motorcycle studies have also evaluated low-percentage ethanol–gasoline blends under fuel-injected operating conditions [3].

HHO-System Configuration

A wet-cell electrolyzer was used to generate HHO gas during all experimental conditions. Wet-cell electrolyzers and intake delivery of oxyhydrogen gas have also been applied in related fuel-injected motorcycle and gasoline-engine studies [7]–[9]. The principal specifications of the electrolyzer and its intake-delivery configuration are presented in Table 3.

Table 3. Specifications and intake-delivery configuration of the HHO electrolyzer

Parameter	Specification
Electrolyzer type	Wet cell
Electrode material	Stainless steel
Number of plates	Four plates
Electrolyte	0.5 L distilled water + 5 g $NaHCO_3$
Water pH	6–8.5
Operating voltage	5.8 V
HHO delivery location	Intake manifold near the fuel injector
Delivery method	Needle injector

The generated HHO gas was delivered to the intake manifold through a needle injector positioned near the fuel injector. The same electrolyzer, electrolyte specification, operating voltage, and delivery arrangement were used for all fuel formulations.

Electrical current, HHO production rate, gas-flow rate, and electrical power input were not measured. Consequently, the actual HHO delivery rate and energy contribution could not be quantified. The HHO apparatus was therefore treated as a common system configuration rather than an independently evaluated experimental factor.

Exhaust-Gas Measurement Instrument

Exhaust-gas characteristics were measured using an HG-520 four-gas analyzer. The instrument directly measured CO, HC, CO_2, and O_2, whereas λ and AFR were calculated by the analyzer system. Accordingly, λ and AFR were treated as analyzer-reported parameters rather than independently measured variables.

The reported measurement ranges and resolutions were:

- CO: 0–9.99%, with a resolution of 0.01%;
- HC: 0–9999 ppm, with a resolution of 1 ppm;
- CO_2: 0–20.0%, with a resolution of 0.01%; and
- O_2: 0–25.00%, with a resolution of 0.01%.

The analyzer provided λ values over a range of 0–2.000 and AFR values over a range of 0–99.0. Its reported response time was approximately 10 s, and the required preheating period was 3–8 min. Automatic zero calibration was performed before the measurements.

No additional calibration procedure using certified reference gas was documented in the available experimental record. The stoichiometric air–fuel ratio or fuel-specific setting used internally by the analyzer to calculate AFR was also not available. Therefore, the reported AFR values should be interpreted as analyzer-calculated outputs and not as independently verified blend-specific air–fuel ratios.

Experimental Procedure

The experiments were conducted under stationary engine operation at target speeds of 1500, 4000, and 7000 rpm. These speeds were selected to represent different stationary operating conditions of the motorcycle engine. Before measurement, the analyzer was preheated and automatically zero-calibrated. The motorcycle engine was then operated until it reached a stable condition. Throttle opening was adjusted to reach and maintain the required engine speed before the exhaust-gas readings were recorded. Each fuel–speed condition was represented by three replicate runs. Between replicate runs, the engine was switched off and allowed to cool before the next measurement. The same motorcycle, HHO-system configuration, analyzer, target engine speeds, and measurement procedure were used for all fuel formulations to support direct descriptive comparison.

Data Analysis

The experimental data were analyzed using descriptive quantitative methods. For each fuel formulation and engine-speed condition, the three replicate measurements were used to calculate the arithmetic mean and standard deviation. The results were expressed as mean ± standard deviation (SD) to present the central measured value and the dispersion among replicate runs. No inferential statistical test was applied. Accordingly, comparisons among fuel formulations were interpreted descriptively and were not used to establish statistical significance or causal effects.

RESULTS AND DISCUSSION

Results

Results are reported as mean ± SD from three replicate runs (n=3) for each fuel formulation at 1500, 4000, and 7000 rpm. CO, HC, CO_2, and O_2 were measured directly, whereas λ and AFR were calculated by the analyzer. Because the same HHO-system configuration was used throughout, the comparisons describe formulation- and speed-specific exhaust-gas responses rather than the independent effect of HHO supplementation.

Carbon Monoxide Concentrations

The mean CO concentrations recorded for the five fuel formulations at each engine speed are presented in Table 4.

Table 4. Exhaust CO concentrations of Pertamax–bioethanol blends at different engine speeds (mean ± SD, n = 3)

Fuel	1500 rpm (%)	4000 rpm (%)	7000 rpm (%)
E0	0.383 ± 0.158	0.037 ± 0.024	0.160 ± 0.156
E5-SC	0.240 ± 0.118	0.020 ± 0.010	0.180 ± 0.156
E10-SC	0.417 ± 0.254	0.010 ± 0.000	0.063 ± 0.023
E5-PW	0.197 ± 0.166	0.030 ± 0.020	0.090 ± 0.045
E10-PW	0.263 ± 0.305	0.023 ± 0.012	0.043 ± 0.021

The corresponding mean values and SD error bars are shown in Figure 1.

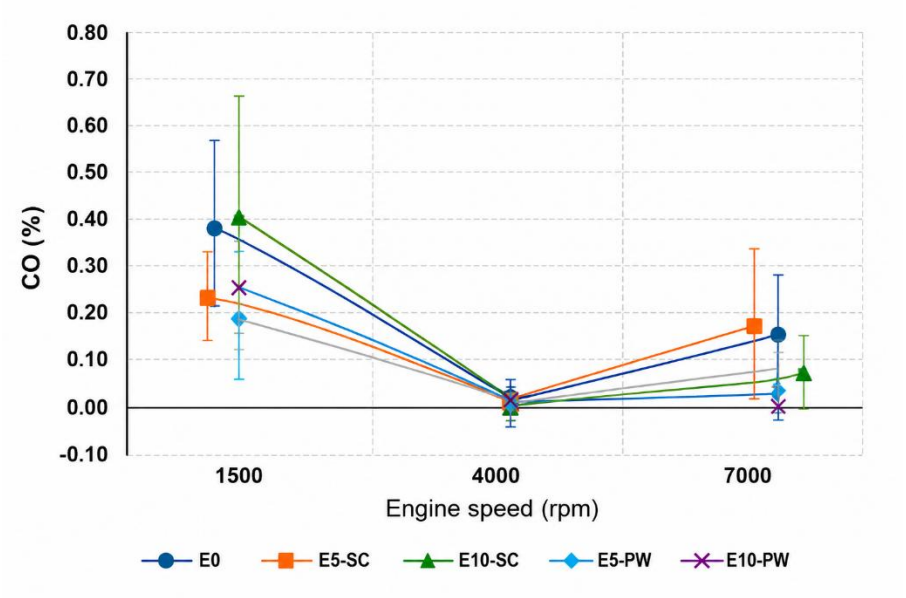

Figure 1. Mean exhaust CO concentrations of Pertamax–bioethanol blends at different engine speeds. Error bars represent SD (n=3).

At 1500 rpm, the mean CO concentrations ranged from 0.197% for E5-PW to 0.417% for E10-SC. At 4000 rpm, all bioethanol blends had lower mean CO concentrations than E0, which recorded 0.037%. The lowest mean at this speed was obtained for E10-SC at 0.010%. At 7000 rpm, the mean CO concentrations ranged from 0.043% for E10-PW to 0.180% for E5-SC. Thus, the formulation with the lowest mean CO concentration differed among the three engine-speed conditions. Several CO conditions, particularly at 1500 rpm, exhibited SD values that were large relative to their corresponding means. Therefore, the comparisons identify differences among the observed mean values but do not establish statistically reliable differences among the fuel formulations.

Hydrocarbon Concentrations

The HC concentrations recorded for each fuel formulation and engine speed are summarized in Table 5.

Table 5. Exhaust HC concentrations of Pertamax–bioethanol blends at different engine speeds (mean ± SD, n = 3)

Fuel	1500 rpm (ppm)	4000 rpm (ppm)	7000 rpm (ppm)
E0	377.67 ± 96.87	210.00 ± 83.57	93.67 ± 24.51
E5-SC	384.33 ± 32.51	137.00 ± 41.21	92.00 ± 10.54
E10-SC	337.67 ± 219.68	129.33 ± 40.37	54.67 ± 7.51
E5-PW	427.67 ± 236.34	142.67 ± 33.89	71.67 ± 2.89
E10-PW	291.67 ± 221.89	114.33 ± 48.53	81.67 ± 19.47

Figure 2 presents the corresponding HC profiles and measurement variation across the three engine speeds.

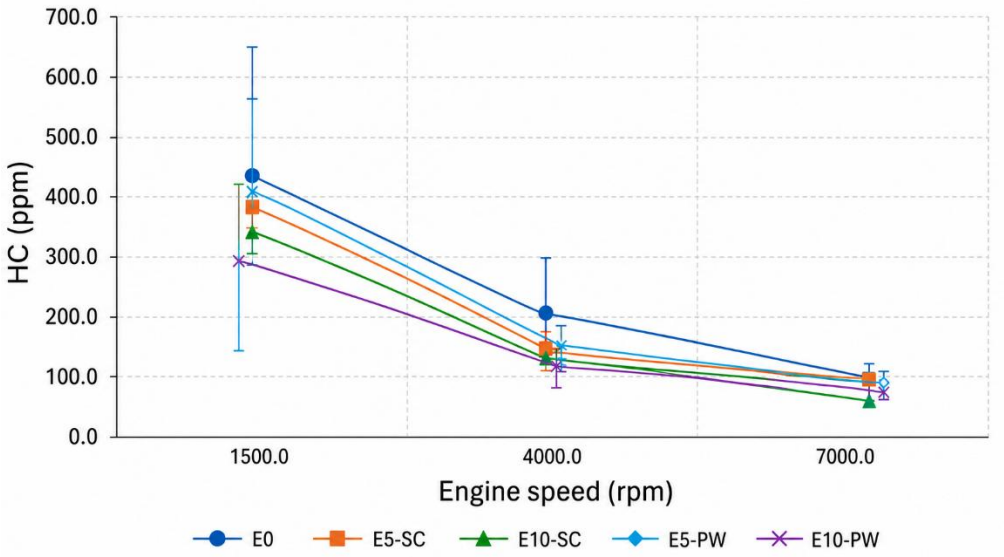

Figure 2. Mean exhaust HC concentrations of Pertamax–bioethanol blends at different engine speeds. Error bars represent SD (n = 3).

For every fuel formulation, the mean HC concentration decreased sequentially as the engine speed increased from 1500 to 4000 and 7000 rpm. At 1500 rpm, E10-PW recorded the lowest mean HC concentration at 291.67 ppm, whereas E5-PW recorded the highest mean at 427.67 ppm. At 4000 rpm, the values ranged from 114.33 ppm for E10-PW to 210.00 ppm for E0. At 7000 rpm, E10-SC recorded the lowest mean HC concentration at 54.67 ppm, which was also the lowest HC value among all tested conditions. The SD values at 1500 rpm exceeded 200 ppm for E10-SC, E5-PW, and E10-PW, indicating relatively wide variation among the three replicate measurements under these conditions.

Carbon Dioxide Concentrations

The CO_2 concentrations obtained for each fuel formulation and engine speed are presented in Table 6.

Table 6. Exhaust CO_2 concentrations of Pertamax–bioethanol blends at different engine speeds (mean ± SD, n = 3)

Fuel	1500 rpm (%)	4000 rpm (%)	7000 rpm (%)
E0	11.667 ± 2.253	12.200 ± 1.020	14.900 ± 0.400
E5-SC	10.567 ± 0.208	13.333 ± 0.709	15.100 ± 0.173
E10-SC	10.267 ± 0.551	13.033 ± 0.666	14.900 ± 0.200

Fuel	1500 rpm (%)	4000 rpm (%)	7000 rpm (%)
E5-PW	10.033 ± 1.097	14.033 ± 0.513	15.000 ± 0.265
E10-PW	10.833 ± 0.404	14.067 ± 1.200	14.467 ± 1.007

The changes in mean CO_2 concentration across engine speeds are shown in Figure 3.

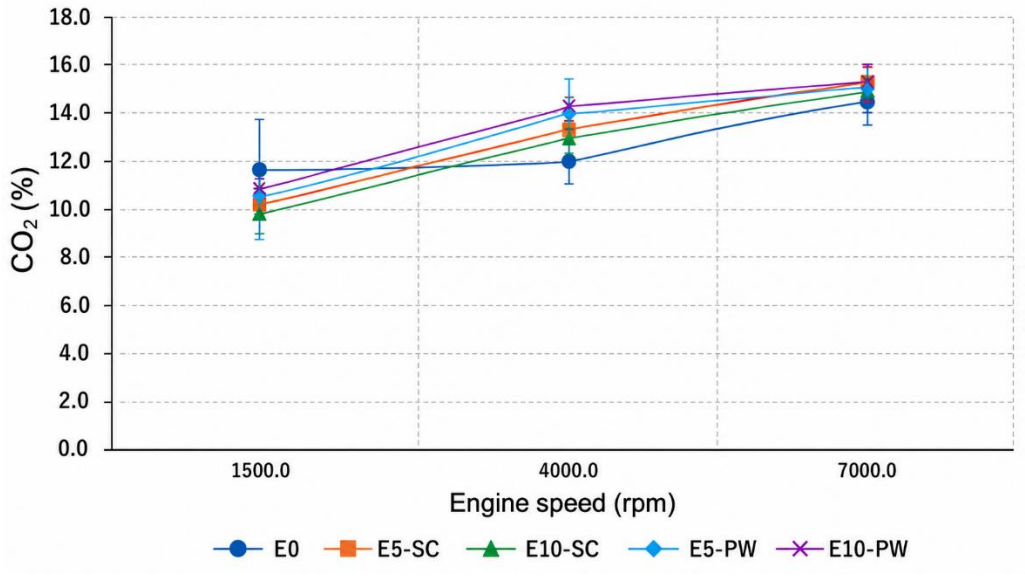

Figure 3. Mean exhaust CO_2 concentrations of Pertamax–bioethanol blends at different engine speeds. Error bars represent SD (n = 3).

The mean CO_2 concentration increased with engine speed for every fuel formulation. At 1500 rpm, the values ranged from 10.033% for E5-PW to 11.667% for E0. At 4000 rpm, the values ranged from 12.200% for E0 to 14.067% for E10-PW. At 7000 rpm, the values ranged from 14.467% for E10-PW to 15.100% for E5-SC. The value recorded for E5-SC at 7000 rpm was the highest mean CO_2 concentration among all tested conditions. These values represent exhaust-gas concentrations rather than total carbon emissions because fuel consumption and exhaust-gas flow rate were not measured.

Oxygen, Lambda, and Air–Fuel Ratio

The O_2, λ, and AFR results for all fuel formulations and engine speeds are summarized in Table 7. O_2 was measured directly by the analyzer, whereas λ and AFR were calculated by the analyzer system.

Table 7. Exhaust O_2 concentration, lambda, and air–fuel ratio of Pertamax–bioethanol blends (mean ± SD, n = 3)

Fuel	Engine speed (rpm)	O_2 (%)	λ	AFR
E0	1500	7.667 ± 3.854	1.374 ± 0.163	20.13 ± 2.38
E0	4000	6.273 ± 4.197	1.349 ± 0.262	19.80 ± 3.85
E0	7000	9.077 ± 5.409	1.385 ± 0.242	20.30 ± 3.31
E5-SC	1500	7.407 ± 2.636	1.540 ± 0.289	22.60 ± 4.25
E5-SC	4000	9.033 ± 2.998	1.445 ± 0.139	21.20 ± 2.07
E5-SC	7000	10.493 ± 2.090	1.458 ± 0.087	21.40 ± 1.31
E10-SC	1500	8.500 ± 4.467	1.495 ± 0.291	21.93 ± 4.31
E10-SC	4000	10.420 ± 3.116	1.538 ± 0.164	22.57 ± 2.41
E10-SC	7000	10.773 ± 4.652	1.489 ± 0.220	21.83 ± 3.24

Fuel	Engine speed (rpm)	O_2 (%)	λ	AFR
E5-PW	1500	12.843 ± 0.961	1.806 ± 0.072	26.50 ± 1.04
E5-PW	4000	13.837 ± 2.166	1.654 ± 0.092	24.23 ± 1.36
E5-PW	7000	13.920 ± 1.242	1.566 ± 0.117	23.00 ± 1.71
E10-PW	1500	10.097 ± 2.111	1.585 ± 0.102	23.27 ± 1.53
E10-PW	4000	9.883 ± 1.545	1.478 ± 0.119	21.67 ± 1.72
E10-PW	7000	9.270 ± 4.048	1.442 ± 0.232	21.17 ± 3.38

Across all tested conditions, the mean O_2 concentrations ranged from 6.273% for E0 at 4000 rpm to 13.920% for E5-PW at 7000 rpm. The analyzer-reported λ values ranged from 1.349 for E0 at 4000 rpm to 1.806 for E5-PW at 1500 rpm, while the analyzer-reported AFR values ranged from 19.80 to 26.50 under the same respective conditions.

All analyzer-reported mean λ values were greater than 1.0. E5-PW recorded the highest mean O_2, λ, and AFR values at each engine speed. Both pineapple waste-derived formulations also recorded higher analyzer-reported λ and AFR values than E0 at all tested speeds. Because λ and AFR were calculated by the analyzer, these values are presented as analyzer outputs rather than independently verified blend-specific mixture ratios.

Overall, the formulation associated with the lowest mean CO or HC concentration varied with engine speed. E5-PW recorded the lowest mean CO concentration at 1500 rpm, E10-SC at 4000 rpm, and E10-PW at 7000 rpm. For HC, E10-PW recorded the lowest mean concentrations at 1500 and 4000 rpm, whereas E10-SC recorded the lowest mean at 7000 rpm. The rankings of O_2, analyzer-reported λ, and analyzer-reported AFR followed different formulation-specific patterns and should not be interpreted using the same lower-is-better criterion applied to CO and HC.

Discussion

The observed exhaust-gas responses varied across the tested fuel formulations and engine-speed conditions. As shown in Figures 1–3 and Table 7, the formulations associated with the lowest mean CO and HC concentrations differed by engine speed, whereas O_2, analyzer-reported λ, and analyzer-reported AFR followed separate formulation-specific patterns. These parameter-specific responses are consistent with evidence that ethanol–gasoline blends do not produce uniform emission changes across different engines and operating points [1], [2]. Nevertheless, the present findings should be interpreted descriptively because each condition was represented by three replicate runs, several conditions exhibited relatively wide SD values, and no inferential statistical test was applied.

Figure 1 shows that all four bioethanol blends produced lower mean CO concentrations than E0 at 4000 rpm. E10-SC recorded the lowest mean CO concentration at this speed, whereas E10-PW recorded the lowest mean at 7000 rpm. However, the pattern was not monotonic across all operating conditions. At 1500 rpm, E10-SC produced a higher mean CO concentration than E0, while at 7000 rpm, E5-SC also produced a slightly higher mean than the gasoline baseline. Consequently, increasing the nominal ethanol content from 5% to 10% did not invariably reduce CO under every tested condition.

A possible explanation for the lower mean CO concentrations recorded for several blends is the oxygenated molecular structure of ethanol, which may support the oxidation of carbon-containing intermediates in locally fuel-rich regions. Nevertheless, the practical response also depends on mixture preparation, evaporation, fuel heating value, electronic fuel-injection compensation, combustion temperature, and engine operating condition. Elfasakhany [11] and Yusoff et al. [12] reported that alcohol–gasoline blends can modify CO and other exhaust emissions, although the direction and magnitude of the response depend on fuel composition

and engine conditions. Experimental studies by Dhande et al. [13] and Mohammed et al. [14] similarly identified operating-condition-dependent changes in combustion and emissions when bioethanol was blended with gasoline. Earlier work by Koç et al. [15] and more recent vehicle-engine testing by Gajewski et al. [16] further showed that increasing ethanol concentration does not necessarily produce a uniform emission response. Iodice et al. [17] demonstrated additional sensitivity during cold-start operation, while Rimkus et al. [18] highlighted broader trade-offs among ethanol concentration, fuel properties, mixture requirements, and engine sustainability. Collectively, these studies support the interpretation that nominal ethanol content alone is insufficient to predict the CO response of a fuel-injected spark-ignition engine.

Across the pollutant and mixture indicators, the descriptive differences between E5-SC, E10-SC, E5-PW, and E10-PW should not be interpreted as direct evidence that biomass origin caused the observed patterns. Sugarcane bagasse is a lignocellulosic material that generally requires pretreatment and hydrolysis before fermentation, whereas pineapple waste contains a different carbohydrate matrix and may follow a different processing route [4]–[6]. Reviews of lignocellulosic pretreatment by Alvira et al. [19] and Taherzadeh and Karimi [20] further demonstrate that biomass structure and processing conditions can affect the accessibility of fermentable sugars and the characteristics of the resulting ethanol. These processing differences could influence water content, acidity, density, residual compounds, volatility, and other fuel properties. However, the present study reported only a nominal ethanol purity of 95% and did not characterize these properties. Accordingly, the data demonstrate formulation-specific descriptive responses but do not establish feedstock origin as the causal mechanism.

The HC patterns in Figure 2 provide a clearer engine-speed trend than the CO results. Mean HC concentration decreased sequentially from 1500 to 4000 and 7000 rpm for all five formulations. E10-PW recorded the lowest mean HC concentrations at 1500 and 4000 rpm, whereas E10-SC produced the lowest mean at 7000 rpm. The lower HC concentrations at higher engine speeds may reflect changes in charge motion, fuel atomization, combustion-chamber temperature, flame propagation, and the oxidation of fuel retained in crevice or quench regions. These possible mechanisms are consistent with the spark-ignition-engine combustion principles described by Heywood [21] and Stone [22]. However, because these combustion processes were not measured directly in the present experiment, they should be treated as possible explanations rather than demonstrated causes.

The interpretation of the HC results must also account for measurement variability. At 1500 rpm, the SD values exceeded 200 ppm for E10-SC, E5-PW, and E10-PW. These values show greater dispersion among the replicate HC measurements at 1500 rpm than at 7000 rpm. Consequently, the lower mean recorded by E10-PW at 1500 rpm should not be treated as evidence of statistical superiority. By contrast, the substantially narrower SD values at 7000 rpm indicate less dispersion among the replicate measurements under that stationary operating condition. Previous ethanol–gasoline studies have likewise shown that HC responses can vary with engine temperature, speed, blend composition, and mixture-control characteristics rather than following a single linear relationship with ethanol percentage [1], [13], [15]–[18].

Figure 3 shows that the mean CO_2 concentration increased with engine speed for every formulation. E5-SC produced the highest mean CO_2 concentration at 7000 rpm, while E5-PW produced the lowest mean at 1500 rpm. A higher CO_2 concentration may accompany a greater proportion of carbon being oxidized to CO_2 within the sampled exhaust gas. However, it does not independently demonstrate greater combustion efficiency or lower environmental impact. Exhaust CO_2 concentration is affected by mixture dilution, residual oxygen, exhaust composition, fuel carbon content, and operating condition [12], [16]–[18], [21], [22]. Because

neither fuel consumption nor exhaust-gas mass flow was measured, the present CO_2 data cannot be converted into total carbon release, brake-specific emissions, or emissions per unit distance.

Table 7 provides additional context for interpreting the CO, HC, and CO_2 results. All mean λ values exceeded 1.0, indicating that the analyzer reported excess-air conditions throughout the tests. E5-PW recorded the highest mean O_2, λ, and AFR values at all three engine speeds. Nevertheless, it did not consistently produce the lowest CO or HC concentration. Within the present dataset, this pattern indicates that a higher residual O_2 concentration or analyzer-reported λ value did not automatically coincide with the lowest CO or HC concentration. Under lean conditions, greater oxygen availability may support oxidation; however, excessive mixture dilution can also affect flame development, cyclic stability, and combustion completeness [21], [22].

AFR should be interpreted cautiously because it was calculated by the gas analyzer rather than measured independently. Its numerical pattern closely followed λ, indicating that the two outputs were mathematically related within the analyzer system. The fuel-specific stoichiometric setting used by the HG-520 was not available in the experimental record. Therefore, the reported AFR values cannot be verified as exact blend-specific air–fuel ratios for E0, E5, and E10. They should instead be interpreted as analyzer-reported mixture indicators. Recent research involving E0–E70 blends similarly emphasizes that ethanol concentration alters fuel properties, stoichiometric requirements, and emission–performance trade-offs [18]. Accordingly, O_2, analyzer-reported λ, and analyzer-reported AFR should be considered complementary indicators and not independent evidence that one fuel formulation achieved better combustion.

The present findings can also be interpreted alongside applied motorcycle-engine studies showing that measured fuel and emission responses are configuration-specific. A previous fuel-injected motorcycle study reported that bioethanol blending changed fuel consumption and exhaust-gas characteristics [3]. Wahyudi et al. [7] examined the response of a fuel-injected motorcycle to electrolyzer installation. Other Motivection studies subsequently evaluated the effects of compression-ratio modification [23] and ignition-system configuration [24] on motorcycle-engine responses. Although these studies differed in fuel, engine, treatment, and measured outputs, they collectively indicate that the observed performance and emission characteristics are closely associated with the specific engine and experimental configuration. This supports the decision not to generalize the ranking of E5-SC, E10-SC, E5-PW, and E10-PW beyond the tested Honda BeAT engine and stationary operating conditions.

The HHO configuration requires a separate interpretive boundary. In the present study, the same wet-cell electrolyzer arrangement, electrolyte composition, nominal operating voltage, and intake-delivery location were used for all fuel formulations. Therefore, HHO formed part of the common experimental environment. However, the absence of a non-HHO control means that none of the differences shown in Figures 1–3 or Table 7 can be attributed independently to HHO supplementation. Earlier experimental and theoretical studies have shown that hydrogen- or oxyhydrogen-assisted responses vary with hydrogen concentration, mixture conditions, engine load, and system configuration [8]–[10].

This limitation distinguishes the present design from studies that deliberately controlled hydrogen or HHO supply and compared assisted and unassisted operation. Rimkus et al. [25] quantified HHO delivery and mixture conditions when evaluating gasoline–bioethanol blends. Purayil et al. [26] further emphasized through a review of hydrogen–gasoline dual-fuel engines that engine responses depend on hydrogen fraction, mixture leanness, ignition timing, operating point, and engine load. Oral [27] investigated gasoline and gasoline–ethanol operation in a hydrogen-generator-supported spark-ignition engine, while Gad and El Soly [28]

compared oxyhydrogen systems with different configurations. Butt et al. [29] demonstrated that the electrical input and gas-production characteristics of an HHO generator must be evaluated together when assessing system performance. Musmar and Al-Rousan [30] also compared gasoline-engine emissions under defined HHO-assisted conditions. These studies demonstrate that HHO flow rate, gas composition, electrolyzer configuration, and electrical energy input must be measured before the independent contribution of HHO can be determined.

Taken together, the findings indicate a trade-off rather than a universally superior fuel. E10-SC was associated with the lowest mean CO concentration at 4000 rpm and the lowest mean HC concentration at 7000 rpm, whereas E10-PW produced the lowest mean CO concentration at 7000 rpm. E10-PW also produced the lowest mean HC concentrations at 1500 and 4000 rpm. In contrast, E5-PW produced the highest λ, AFR, and O_2 values but was not the formulation with the lowest CO or HC concentration under every condition. The practical contribution of the study is therefore the identification of condition-specific exhaust-gas patterns for two waste-derived bioethanol formulations in the same small fuel-injected motorcycle. The results do not establish an optimal formulation for all operating conditions.

From an application perspective, fuel selection should not be based on a single exhaust parameter. CO and HC represent different incomplete-combustion products, CO_2 is reported only as an exhaust-gas concentration, and λ, AFR, and O_2 describe mixture-related conditions rather than environmental performance by themselves. A formulation that produces the lowest CO concentration at one engine speed may not produce the lowest HC concentration or maintain the same ranking at another speed. A multi-parameter evaluation is therefore necessary when screening waste-derived bioethanol blends for motorcycle applications.

Several methodological details could not be fully evaluated from the available experimental record. The production pathway and detailed physicochemical properties of the two bioethanol samples were not documented beyond their reported feedstock origin and nominal purity. In addition, the procedures used to control residual-fuel carryover between formulations, the stationary engine-load configuration, and the detailed exhaust-gas sampling protocol were not specified. Only automatic zero calibration of the analyzer was documented, while the fuel-specific stoichiometric setting used to calculate AFR was unavailable. These limitations restrict methodological replication and require cautious interpretation of formulation-specific differences.

Future research should characterize the water content, density, acidity, lower heating value, and composition of each bioethanol sample before blending. The experimental design should include randomized test order, a documented fuel-system flushing procedure, controlled engine temperature and load, and a larger number of replicate runs. A non-HHO condition should also be included, together with measurements of electrolyzer current, voltage, gas-flow rate, gas composition, and electrical energy consumption. Measuring torque, power, fuel consumption, exhaust-gas flow, and combustion-related parameters would permit performance and mass-based emission analyses. These additions would help distinguish the effects of fuel formulation from those of HHO supplementation and provide a stronger basis for statistical comparison and practical fuel selection.

CONCLUSION

This study compared the exhaust-gas characteristics of Pertamax blended with sugarcane bagasse- and pineapple waste-derived bioethanol in a fuel-injected motorcycle operated under a common HHO-system configuration. E10-SC recorded the lowest mean CO concentration at 4000 rpm and the lowest mean HC concentration at 7000 rpm, whereas E10-PW recorded the lowest mean CO concentration at 7000 rpm. However, no formulation consistently recorded

the lowest mean CO and HC concentrations across all engine speeds. O_2 and the analyzer-reported λ and AFR values followed different formulation-specific patterns and should be interpreted as complementary mixture indicators rather than direct measures of overall emission performance.

The study provides a descriptive comparison of two waste-derived bioethanol formulations tested using the same motorcycle and nominal experimental configuration. The results do not establish statistical superiority, a universally optimal formulation, or a causal effect of bioethanol feedstock origin. The independent contribution of HHO also could not be determined because no non-HHO control was included and HHO flow rate, electrical input, and energy consumption were not measured.

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